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AFOSR-TR- 90-0636

THE OHIO STATE UNIVERSITY

AD-A221 682

Laser Diagnostics of Plasma Thrusters

Thomas M. York
Department of Aeronautical & Astronautical Engineering

U.S. Air Force
Air Force Office of Scientific Research
Bolling Air Force Base, D.C. 20332

Grant No. AFOSR-89-0120
Final Report

April 1990

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RF Project 767158/721632

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
1 April 1990

3. REPORT TYPE AND DATES COVERED
FINAL - 01 Dec 88-30 Nov 89 /DURIP

4. TITLE AND SUBTITLE
"IR AND FIR LASER DIAGNOSTICS FOR PLASMA THRUSTERS USING A CW CO_2 RADIATION SOURCE" (U)

5. FUNDING NUMBERS
PE- 61102F
PR- 2308
TA- A1

6. AUTHOR(S)

Dr Thomas M. York

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Columbus, OH 43210-1276

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NA - Bldg 410
Bolling AFB, D.C. 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFOSR-89-0120

11. SUPPLEMENTARY NOTES

AFOSR-[illegible] 90-068

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The research involves diagnostics studies of plasma thrusters. These devices generate ionized gases which are accelerated at thermal and electromagnetic modes. The research effort uses the new, high resolution diagnostic techniques that will determine electron densities, local magnetic fields and density fluctuations indicating anomalous transport. A long wavelength carbon dioxide laser which allows more sensitive measurements, with its long wavelength, is used. The laser will be coupled with a Far infrared Laser System capable of generating beams around ten milliwatt levels, and provide a diagnostic study that has not yet been used in thruster plasma diagnosis.

14. SUBJECT TERMS

Laser Diagnostics, Multi-Beam Interferometry, Fluctuation

15. NUMBER OF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
U	U	U	U

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FINAL REPORT

of work carried out under

Grant No. AFOSR-89-0120

under

Defense University Research Instrumentation Program (1988)

titled

Laser Diagnostics of Plasma Thrusters

for the period

01 Dec 1988 through 30 Nov 1989

Submitted to

Mitat A. Birkan, Program Manager
Air Force Office of Scientific Research
Directorate of Aerospace Sciences
AFOSR/NA, Building 410
Bolling AFB, DC 20332-6448

by

Prof. Thomas M. York
Ohio State University Research Foundation
1314 Kinnear Road
Columbus, OH 43212-1994

Report Requirements

Grantee will provide one (1) copy of a final report sixty (60) days after completion of the grant which will identify the equipment actually acquired (although it might vary with that described in the grant) by name, manufacturer where possible, costs, and describe any special circumstances regarding the acquisition or changes to the equipment list. The final report will also include a concise summary of the research projects on which the equipment has been or will be used, including support of (a) the research work described in the proposal and (b) other research work of interest to the DoD.

EQUIPMENT REPORT

EQUIPMENT RELATED TO THE LASER SYSTEM

1)	Name:	CO_2/FIR Laser System	
	Manufacturer:	Apollo Lasers Inc. 9201 Independence Ave. Chatsworth, CA 91311	
	Model:	122	
2)	Name:	Cooling Unit for Apollo's Model 122	
	Manufacturer:	NESLAB Instruments Inc. P.O. Box 1178 Portsmouth, NH 03801	
	Model:	RTE-110B	
3)	Name:	CO_2 Power Meter	
	Manufacturer:	Apollo Lasers Inc. 9201 Independence Ave. Chatsworth, CA 91311	
	Model:	101	
	Cost:	(Total cost for items 1-3)	$78,385

MULTI-BEAM INTERFEROMETRY EXPERIMENT

4)	Name:	Acousto-Optic Modulator	
	Manufacturer:	Intra-Action Corp. 3719 Warren Ave. Bellwood, IL 60104	
	Model:	AGM-406B	
	Cost:		$2,595
5)	Name:	Acousto-Optical Modulator Driver	
	Manufacturer:	Intra-Action Corp. 3719 Warren Ave. Bellwood, IL 60104	
	Model:	GE-4030S	
	Cost:		$1,875
6)	Name:	Down Collimator	
	Manufacturer:	Optics for Research Box 82 Caldwell, NJ 07006	
	Model:	ELZ-25-1.6X	
	Cost:		$2,000

7)	Name:	Beam Selector	
	Manufacturer:	Melles Griot 1770 Kettering Street Irvine, CA 92714	
	Model:	12-BDZ-003	
	Cost:		$399
8)	Name:	Mirrors, Beamsplitters, Lenses	
	Manufacturer:	Optics for Research Box 82 Caldwell, NJ 07006	
	Model:		
	Cost:		$7,920
9)	Name:	Mirror/Beamsplitter/Lens Mounts	
	Manufacturer:	Newport 18235 Mt. Baldy Circle Fountain Valley, CA 92708-8020	
	Model:		
	Cost:		$3,038
10)	Name:	CO_2 Radiation Detectors/Pre-Amps/Amps	
	Manufacturer:	Electro-Optical Systems Inc. 1000 Nutt Road Pheonixville, PA 19460	
	Model:	MCT10-T1-020	
	Cost:		$9,600
11)	Name:	Phase Comparators	
	Manufacturer:	Merrimac Industries Inc. P.O. Box 986 41 Fairfield Place West Caldwell, NJ 07007-0986	
	Model:	PCM-3-40B	
	Cost:		$4,600

DATA AQUISITION SYSTEM

12)	Name:	IBM Compatible Personal Computer	
	Manufacturer:	DELL Computer Corp. 9505 Arboretum Blvd. Austin, TX 78759-7299	
	Model:	System 316SX	
	Cost:		$3,317

13)	Name:	ASYST 3.0 Scientific Software	
	Manufacturer:	Asyst Software Technologies Inc. 100 Corporate Woods Rochester, NY 14623	
	Model:	ASYST 3.0 Modules 1,2,4	
	Cost:		$1,571
14)	Name:	IEEE-488 Interface Board	
	Manufacturer:	Metrabyte Corp. 440 Myles Standish Blvd. Taunton, MA 02780	
	Model:	IE-488	
	Cost:		$399
15)	Name:	Cable for IEEE Communications	
	Manufacturer:	Metrabyte Corp. 440 Myles Standish Blvd. Taunton, MA 02780	
	Model:	C88-01	
	Cost:		$75
16)	Name:	Eight Channel Waveform Recorder	
	Manufacturer:	Gould Electronics 432 Windsor Park Drive Dayton, OH 45459	
	Model:	13-G4386-2	
	Cost:		$4,995

CO_2 BEAM QUALITY INVESTIGATION EQUIPMENT

17)	Name:	CO_2 Spectrum Analyzer	
	Manufacturer:	Optical Engineering 3300 Coffey Lane Santa Rosa, CA 95403	
	Model:	16A	
	Cost:		$2,420
18)	Name:	Laser Power Probe with Carrying Case	
	Manufacturer:	Optical Engineering 3300 Coffey Lane Santa Rosa, CA 95403	
	Model:	P-50Y	
	Cost:		$240

19)	Name:	CO_2 Beam Probes	
	Manufacturer:	Optical Engineering 3300 Coffey Lane Santa Rosa, CA 95403	
	Model:		
	Cost:		$206
20)	Name:	Motorized Drive, Translation Stage, Controller Interconnecting Cable	
	Manufacturer:	Newport 18235 Mt. Baldy Circle Fountain Valley, CA 92708-8020	
	Model:		
	Cost:		$771
21)	Name:	CO_2 Radiation Detector Element	
	Manufacturer:	EDO Corp. Barns Engineering Division 88 Long Hill Cross Roads P.O. Box 867 Shelton, CT 06484-0867	
	Model:	350-1	
	Cost:		$79
22)	Name:	CO_2/FIR Power Meter Head	
	Manufacturer:	Scientech 5649 Arapahoe Ave. Boulder, CO 80303	
	Model:	36-001	
	Cost:		$620

OTHER INSTRUMENTS

23)	Name:	Function Generator (Used)	
	Manufacturer:	Wavetek Leasametric 103 Chesley Drive, Suite 6 Media, PA 19036	
	Model:	166	
	Cost:		$2,295
	Total		$127,400
	The Ohio State University Contribution		$39,109
	AFOSR Contribution		$88,291

SUMMARY OF EQUIPMENT USE
ON RESEARCH PROJECTS

IR AND FIR LASER DIAGNOSTICS FOR PLASMA THRUSTERS USING A CW CO_2 RADIATION SOURCE

(AFOSR Grant No. 89-0297)

Principal Investigator: Dr. Thomas M. York

SUMMARY/OVERVIEW

The research will involve diagnostic studies of plasma thrusters. These devices generate ionized gases which are accelerated at thermal and electromagnetic modes. The research effo t will use the new, high resolution diagnostic techniques that will determine electron densities, local magnetic fields and density fluctuations indicating anomalous transport. A long wavelength carbon dioxide laser which allows more sensitive measurements, with its long wavelength, will be used. The laser will be coupled with a Far Infrared Laser System capable of generating beams around ten milliwatt power levels, and provide a diagnostic study that has not yet been used in thruster plasma diagnosis.

TECHNICAL DISCUSSION

Description and Capabilities of Laser Source

The laser system that will be the heart of the diagnostic arrangements is a CO_2 source (Model 570, Apollo Lasers, Chatsworth, CA). This is a tunable system with an output of 30 Watts minimum at 50 or more wavelengths, TEM_{00}. It is capable of 65 W output CW or 200 W pulsed. This laser can also be used to pump an FIR laser (Model 122, Apollo Lasers, Chatsworth, CA). Using methanol, this can operate between 70 μm and 500 μm; at 118.8 μm power levels on the order

of 100 mW CW or 200 mW pulsed are available; beam diameter is 10 mm. These wavelengths and power levels are appropriate for diagnosing the plasmas of interest in the exhaust of plasma thruster, as will be discussed below. Along with the laser, modulating and mixing components in the optical train are critical, as well as detectors at the various wavelengths.

Plasma Properties in the Thruster Exhaust Field

The plasma being ejected from MPD type device has been categorized by a number of research studies. In 1971, NASA-Lewis reported Thomson scattering measurements in the exhaust of a nitrogen MPD: at 20kA, and 11.2kA 30 cm from the exit plane $Ne \approx 8x10^{13}$ cm^{-3}, $Te \approx 5$ eV. With argon, a propellent, a spatial variation of properties was reported by E.M. Campell (Princeton EPL) in 1977, who used Langmuir probes: at 4kA with 12g/Sec, $Ne = 6x10^{14}$ cm^{-3} to 2×10^{13} cm^{-3} between 0 and 30 cm on axis while $Te = 12{,}000°K$ to $4{,}000°K$ between 0 and 30 cm. In 1985, an MPD operated at AFAL was diagnosed with Langmuir probes developed by the principal investigator and indicated $Te \approx 2eV$ at 25 cm, while $Ne = 4.48 \times 10^{15}$ at 20 cm and $Ne = 1.9 \times 10^{15}$ at 30 cm.

Based on the above evaluations, it is anticipated that source plasma generated by 4kA will produce plasmas with $Ne \approx 10^{15}$ cm^{-3}, 4eV and will expand to $Ne \approx 10^{14}$ cm^{-3}, $Te \approx 2eV$ at 30 cm. These are critical values when designing a diagnostic system.

PROPOSED RESEARCH STUDIES

The effort to be carried out will involve three different diagnostic measurements with the CO_2 laser based system: (1) multi-beam interferometry; (2) Faraday-rotation measurements of local B-field; and (3) fluctuation studies.

Each of these has its own inherent difficulty; i.e., this is not an application of off-the-shelf type techniques, but the application of recently reported, physically proven techniques which will require careful experimental design and unique components to produce useful results. Generally, the list above is indicative of increasing difficulty. A one year effort, especially with a significant percentage being carried by a (new) graduate student researcher, must concentrate on the simpler techniques in order to optimize results. Accordingly, some techniques (2 and 3) will receive careful and complete evaluation with respect to experimental design, while emphasis will be directed to accomplishing measurements with the multi-beam interferometer.

Multi-beam Interferometer

This technique generally utilizes a Mach-Zender configuration. A measurement of phase shift (ϕ) allows determination of electron density as

$$\phi = 2.82 \times 10^{-13} \lambda_o \int_{Z1}^{Z2} Ne(Z)dZ \qquad \text{(Cg5 units)}$$

When λ_o is the laser wavelength, Z is the path variable through the plasma. In the above, measurement of ϕ indicates the integrated line density.

Clearly, one can see the importance of CO_2 radiation at $10\mu m$ as compared to say, red light at 6973Å. Also, the unfolding of an axisymetric profile of Ne requires a large number (2-5) of interferometer channels. Successful applications of this technique with CO_2 lasers have produced time histories of profiles of Ne(r) over a period of 20 ms with Ne $\approx 10^{15}$ cm^{-3} and 1 $\approx$ 10 cm. Considerable care will have to be exercised in detector selection to be successful. The use of a Bragg cell to modulate the beam has proven successful and that technique

will be pursued. Care will have to be taken with the beam deflection (α) due to gradients, as $\alpha \sim M_o \lambda_o^2$, and this could cause problems in location of detector windows. Another advantage of large λ_o is that the sensitivity to mechanical vibration decreases; specifically, when $\lambda_o > 4 \times 10^8 [\Delta\epsilon/r_o n_o]$ where $\Delta\epsilon$ is vibration induced path change and r_o is plasma radius.

Faraday Rotation Measurements of B field - Polarimetry

The determination of local, unperturbed magnetic field is quite difficult; all experimenters use physical loops placed in the plasma. This disturbs the signal, cools the plasma, and alters current conduction path. So, a nonintrusive technique is quite valuable. Through Maxwells' equation, the local current density can also be determined.

The basic principle of this measurement is that the plane of polarization of a laser beam will be rotated proportional to B, as

$$\Theta \text{ (deg)} = 1.5 \times 10^{-12} \lambda_o^2 \int_0^l NeB_{11}(kG)dl$$

Clearly, a large λ_o will allow significant Θ to be generated even though B_{11} (the component of B along propagation) will be small. Specifically with $Ne = 10^{15}$ cm^{-3} and $l = 10$ cm, the Θ with CO_2 radiation would be very difficult to measure. However, using 118.8 μm will produce a rotation of greater than 1 degree. It can be seen that the signal involves the product, Ne B_{11}, so the results from the CO_2 measurement of Ne(r) will be critical to accurate determination of B_{11}(r) profiles.

Measurement of Electron Density Fluctuations

This technique is based upon the principles of Thomson scattering - scattering from free elections and ions. The ability to measure fluctuations, which are extremely important because they generate anomalous transport, is related to a number of factors. The characteristic parameter for Thomson Scattering is $\alpha = 1/k\lambda_D = \lambda_o/4\pi\lambda_D \mathrm{Sin}(\theta_s/2)$ where λ_D is the Debye length and θ_s is the scattering angle. The range, $\alpha << 1$, defines normal Thomson Scattering for Te, Ne. When $\alpha >> 1$ plasma waves and thermal ion fluctuations may be studied and ion temperature determined.

Wave scattering can result in large enhancements in the scattered power, well above those achieved with thermal motion, as scattered power is

$$Ps = \tfrac{1}{4} P_o r_e^2 \lambda_o^2 (\tilde{N})^2 Lv$$

Where P_o is incident power, r_e is electron radius, λ_o is incident wavelength, $\tilde{N}$ is defined by $\tilde{N}$ core (kZ-wt) and Lv is the length of the scattering volume. CO_2 lasers with 10-100 W can be used, but also, FIR lasers generating 119 μm at 10-100 mW output power levels have been sufficient to perform scattering measurements with good signal-to-noise ratios. One critical element in the type of measurement is a low-noise fundamental mode mixer. Fluctuation measurements over a range of frequencies have been made with plasmas similar to those expected in MPD exhaust flows.

THE MULTI-BEAM INTERFEROMETRY EXPERIMENT

Up-to-date, the entire multi-beam interferometry experiment has been designed and the individual components of the hardware involved have been ordered. The optical scheme of the multi-beam interferometer is shown in Figure

1. The experiment was initially designed with five independent channels interfering with each other but due to limited funds it will be implemented with only four channels. When money becomes available in the future, the fifth channel will be added.

The output of the CO_2 laser (Apollo Laser, Inc., Model 570) is down-collimated from 8mm diameter to about 5mm and then it enters the germanium acousto-optic cell (Intra-Action Corp., Model AGM-406B). The acousto-optic cell not only splits the input beam into two output beams, the scene beam (zero-order) and the reference beam (first-order), but also shifts the frequency of the reference beam by 40 MHz with respect to the frequency of the scene beam. The first order beam illuminates the five reference paths of the interferometer. The intensity of each reference beam is about 20% of the intensity of the first order beam. After the reference beams leave the reference beamsplitters, they go through the beam recombiners and then they are focused on the detectors. The zero order beams follow the scene beam paths. After the five scene beams leave the scene beamsplitters, they reflect off the flat mirrors and redirected to propagate through the plasma twice. As they exit the plasma, the flat mirrors direct them onto the beam recombiners where they recombine with the reference beams and then they are focused on the detectors.

The power detected by the detectors contains an oscillating component at 40MHz due to the interference between the reference beams with the corresponding scene beams and it is also phase modulated by phi due to the propagation of the beams through the plasma. The block diagram of one receiver is shown in Figure 2. All five receivers are the same as the one shown in Figure 2. The radiation is detected by the thermoelectrically cooled detectors and a signal proportional to the input power is generated. The signal is amplified by a first stage ampli-

fier and an amplifier and then enters the quadrature phase detector. The quadrature phase detector generates two signals, one is proportional to the sine of phi and the other is proportional to the cosine of phi. The major advantage of this technique is that the phase shift phi can be calculated unambiguously because information for both the sin(phi) and the cos(phi) exists. A function generator set at 40MHz drives each one of the five quadrature phase detectors and the acousto-optic cell. A waveform recorder (Gould Electronics, 4386) will be used to digitize and store all the sine and cosine signals while the experiment is in progress. The stored data will then be transferred via a IEEE-488 bus to a PC (Dell System 316SX) for further analysis. The commercially available software ASYST 3.0 will be used for analysis and graphing/presentation purposes.